Final results on $K^+ \to \pi^+ \nu \bar{\nu}$ from BNL E949

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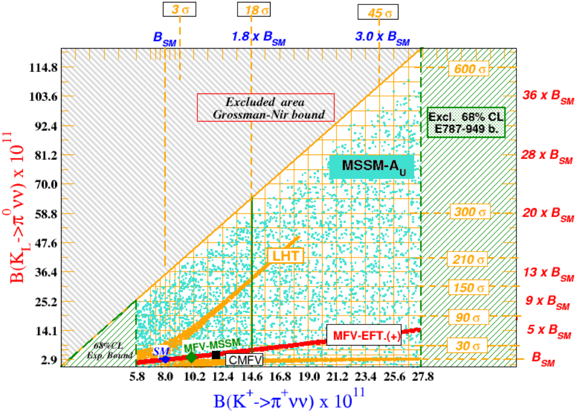
Sensitivity to New Physics

The $K^+ \to \pi^+ \nu\bar{\nu}$ branching ratio can be precisely predicted in the SM (and most models) owing to knowledge of the transition ME from similar processes and minimal long-distance effects.

In the SM, $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (0.85 \pm 0.07) \times 10^{-10}$ (arXiv:0805.4119).



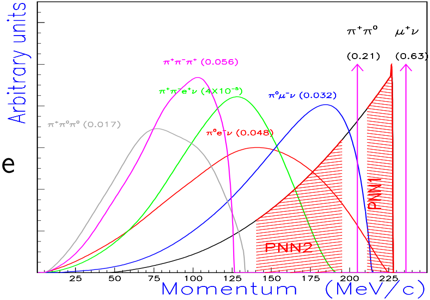
Ref: G.Isidori, arXiv:0801.3039, attributed to Frederico Mescia

Previous $K^+ \to \pi^+ \nu \bar{\nu}$ results

Region	**"PNN2"**	**"PNN1"**
$P(\pi^+)$ MeV/c	[140,195]	[211,229]
Stopped K^+	1.7×10^{12}	7.7×10^{12}
Background events	1.22 ± 0.24	0.45 ± 0.06
Candidate events	1	3
$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$	$< 22 \times 10^{-10}$ (90% CL)	$(1.47^{+1.30}_{-0.89}) \times 10^{-10}$
Reference	PRD**70**, 037102 (2004)	PRD**77**, 052003 (2008)
	E787	E787& E949

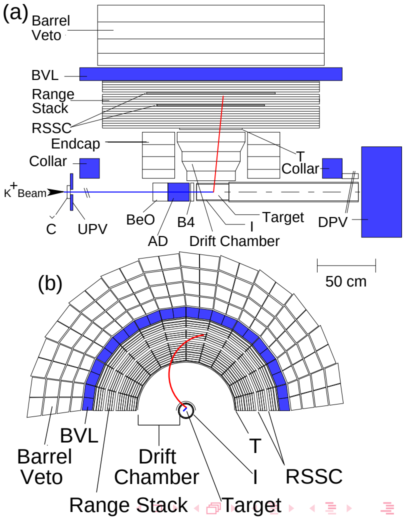
Rate *vs.*

π^+ momentum in K^+ rest frame



E949 experimental method

- **Measure everything possible**
- $\sim 700\ \mathrm{MeV}/c\ \mathrm{K}^+$ beam
- Stop K^+ in scint. fiber target
- Wait at least 2 ns for K^+ decay (delayed coincidence)
- Measure π^+ momentum P in drift chamber
- Measure π^+ range R and energy E in target and range stack (RS)
- Stop π^+ in range stack
- Observe $\pi^+ \to \mu^+ \to e^+$ in RS
- Veto photons, charged tracks
- New/upgraded detector elements compared to E787

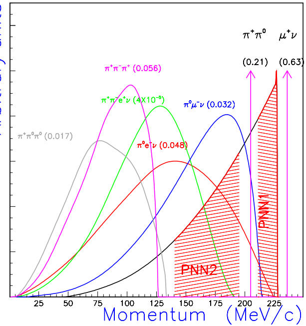


The Secret of Finding Rare Decays - J.Mildenberger (& J.Hart)

E787 and E949 analysis strategy

- A priori identification of background sources.
- Suppress each background with at least two independent cuts.
- It is difficult to simulate background at the 10^{-10} level, so measure background with data by inverting cuts and measuring rejection taking any correlation into account.
- To avoid bias, set cuts using $1/3$ of data, then measure backgrounds with remaining $2/3$ sample.
- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- "Blind analysis". Don't examine signal region until all backgrounds verified.

Backgrounds in the pnn2 region



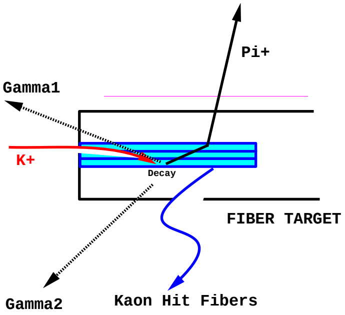
Process	Rate
$K^+ \to \pi^+\nu\bar{\nu}$	0.8×10^{-10}
$K^+ \to \pi^+\pi^0$	$2092000000.0 \times 10^{-10}$
$K^+ \to \pi^+\pi^0\gamma$	$2750000.0 \times 10^{-10}$
$K^+ \to \pi^+\pi^- e^+\nu$	409000.0×10^{-10}
$K^+ \to \mu^+\nu$	$6344000000.0 \times 10^{-10}$
$K^+ \to \mu^+\nu\gamma$	$62000000.0 \times 10^{-10}$
$K^+ \to \mu^+\pi^0\nu$	$332000000.0 \times 10^{-10}$
CEX	$\sim 46000.0 \times 10^{-10}$
Scattered π^+ beam	$\sim 25000000.0 \times 10^{-10}$

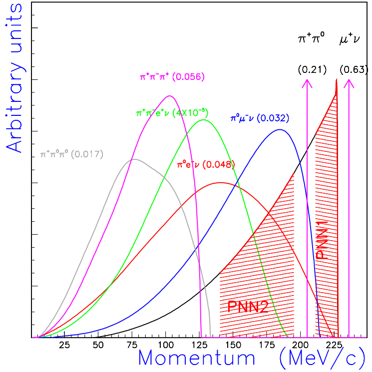
CEX $\equiv (K^+ n \to K^0 X) \times (K^0 \to K^0_L) \times (K^0_L \to \pi^+\mu^-\nu)$

$K^+ n \to K^0 X$ rate is empirically determined.

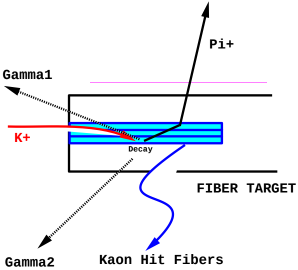
Main pnn2 background: $K^+ \to \pi^+\pi^0$ -scatters

The main background below the $K^+ \to \pi^+\pi^0$ peak is due to $K_{\pi 2}$ decays where the π^+ scatters in the target losing energy simultaneously obscuring the correlation with the π^0 direction.



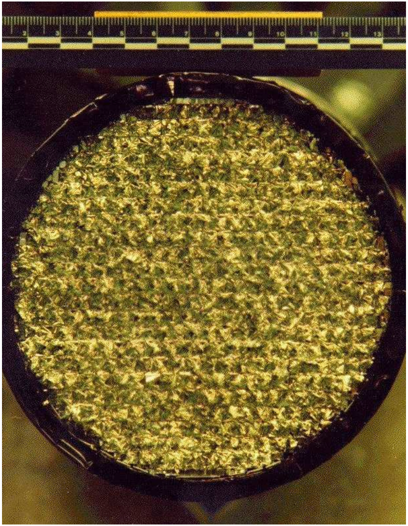


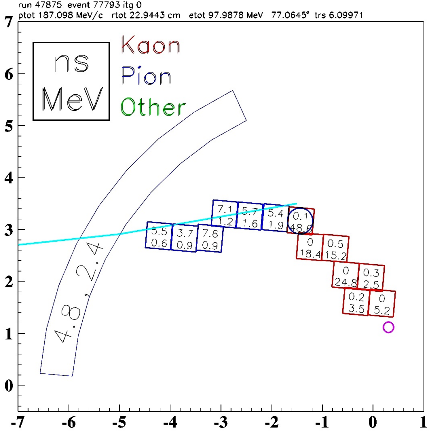
Suppression of $K_{\pi 2}$-scatter background



- Photon veto of $\pi^0 \to \gamma\gamma$
  Photon detection in beam region important
- Identification of π^+ scattering in the target
  - kink in the pattern of target fibers
  - π^+ track that does not point back to the K^+ decay point
  - energy deposits inconsistent with an outgoing π^+
  - unexpected energy deposit in the fibers traversed by the K^+

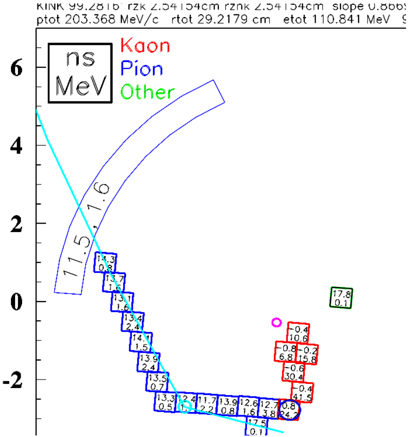
E949 scintillating fiber target



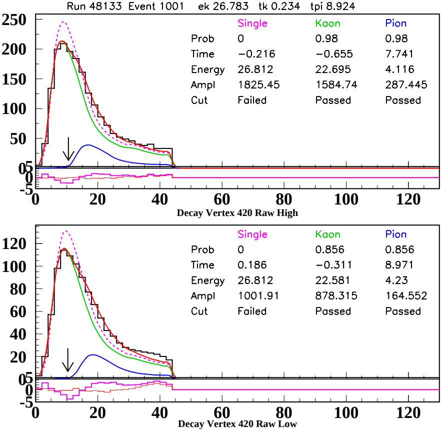


'Typical' pattern in target fibers for $K^+ \to \pi^+\pi^0$ decay.

Identification of π^+ scattering

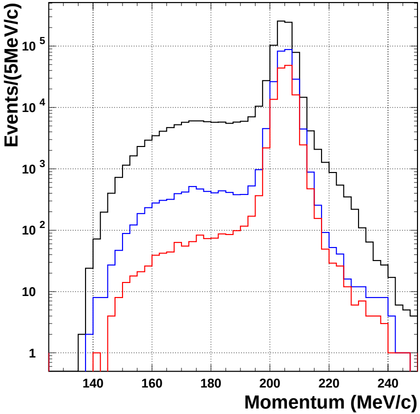


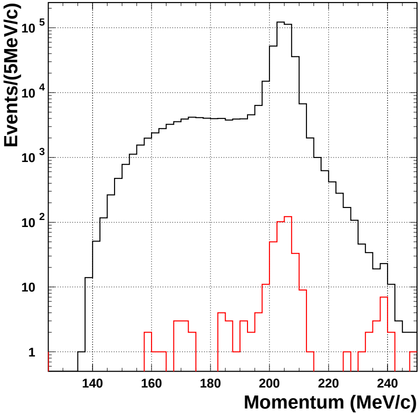
Kink in pattern of target fibers



Excess energy in kaon fibers ("CCDPUL")

Suppression of $K_{\pi 2}$ scatter background





Black: Photon-tagged sample

Blue: After target cuts (except CCDPUL)

Red: After all target cuts

Black: π^+-scatter-tagged sample

Red: After photon veto cuts

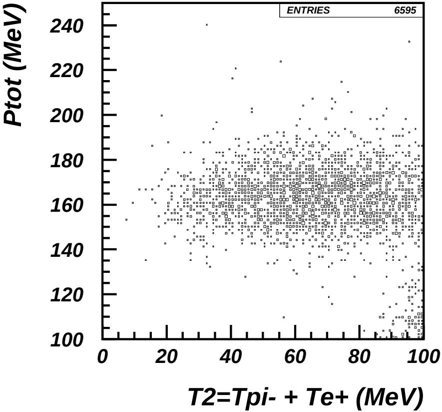
Estimation of $K_{\pi 2}$ scattering background

- $K_{\pi 2}$ scattering background is suppressed by PV and target cuts.
- To estimate PV rejection, multiple π^+ scattering samples are prepared by inverting different combinations of target cuts.
- The "normalization" sample is estimated by inverting the PV cut, but the sample is contaminated with $K_{\pi 2}$ scatters in the range stack (RS) and by $\mathrm{K}^+ \to \pi^+\pi^0\gamma$.

After disentangling the processes:

Process	Background events
$K_{\pi 2}$ TG-scatter	$0.619 \pm 0.150^{+0.067}_{-0.100}$
$K_{\pi 2}$ RS-scatter	$0.030 \pm 0.005 \pm 0.004$
$K_{\pi 2\gamma}$	$0.076 \pm 0.007 \pm 0.006$

$K^+ \to \pi^+\pi^-e^+\nu$ (K_{e4}) background



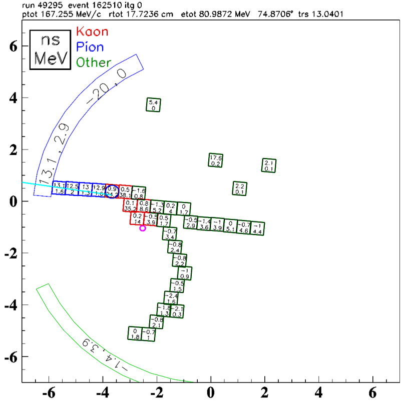
$K^+ \to \pi^+\pi^-e^+\nu$ can be a background if the π^- and e^+ have very little kinetic energy and evade detection.

Figure: π^+ momentum (P_π) *vs.* total kinetic energy of π^- and e^+ from simulated $K^+ \to \pi^+\pi^-e^+\nu$ decays.

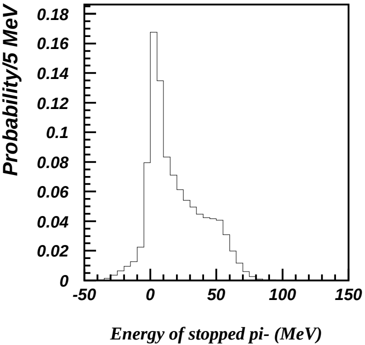
Signal region is $140 < P_\pi < 199$ MeV/c

$K^+ \to \pi^+\pi^- e^+\nu$ background

Isolate K_{e4} sample using target pattern recognition, similar to $K_{\pi 2}$ scatter.



Estimate rejection power of target pattern recognition with simulated data supplemented by measured π^- energy deposition spectrum in scintillator.



Total background and sensitivity

Process	Bkgd events (E949)	Bkgd events (E787)
$K_{\pi 2}$-scatter	$0.649 \pm 0.150^{+0.067}_{-0.100}$	1.030 ± 0.230
$K_{\pi 2\gamma}$	$0.076 \pm 0.007 \pm 0.006$	0.033 ± 0.004
K_{e4}	$0.176 \pm 0.072^{+0.233}_{-0.124}$	0.052 ± 0.041
CEX	$0.013 \pm 0.013^{+0.010}_{-0.003}$	0.024 ± 0.017
Muon	0.011 ± 0.011	0.016 ± 0.011
Beam	0.001 ± 0.001	0.066 ± 0.045
Total bkgd	$0.93 \pm 0.17^{+0.32}_{-0.24}$	1.22 ± 0.24

	E949 pnn2	E787 pnn2
Total Kaons	1.70×10^{12}	1.73×10^{12}
Total Acceptance	1.37×10^{-3}	0.84×10^{-3}
SES	4.3×10^{-10}	6.9×10^{-10}

The branching ratio that corresponds to one event in the absence of background is the Single-Event Sensitivity (SES).

For the E787+E949 pnn1 analysis, SES $= 0.63 \times 10^{-10}$.

Verification of background estimates

Relax PV and CCDPUL cuts to define 2 distinct regions PV_1 and CCD_1 immediately adjacent to the signal region.

Define a third region PV_2 by further loosening of the PV cut.

Compare the observed (N_{obs}) with the expected number (N_{exp}) of events in each region.

Region	N_{exp}	N_{obs}
CCD_1	$0.79^{+0.46}_{-0.51}$	0
PV_1	$9.09^{+1.53}_{-1.32}$	3
PV_2	$32.4^{+12.3}_{-8.1}$	34

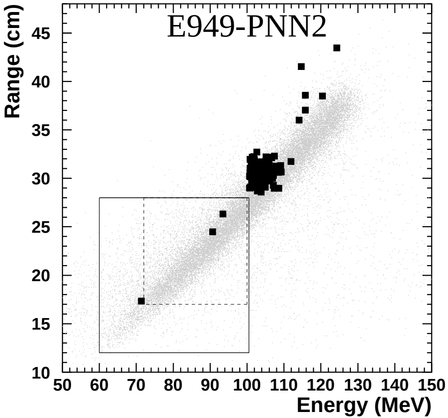
The probability to observe ≤ 3 events when $9.09^{+1.53}_{-1.32}$ are expected is 2%.

The probability of the observation in regions CCD_1 and PV_1 given the expectation is 5%; the expectation is [2%,14%] when the uncertainty in N_{exp} is taken into account.

Division of the signal region

- The background is not uniformly distributed in the signal region.
- Use the remaining rejection power of photon veto, delayed coincidence, $\pi \rightarrow \mu \rightarrow e$ and kinematic cuts to divide the signal region into 9 cells with differing levels of signal acceptance (S_i) and background (B_i).
- Calculate $\mathcal{B}(\mathrm{K}^+ \rightarrow \pi^+\nu\bar{\nu})$ using S_i/B_i of any cells containing events using the likelihood ratio method.

Examining the signal region

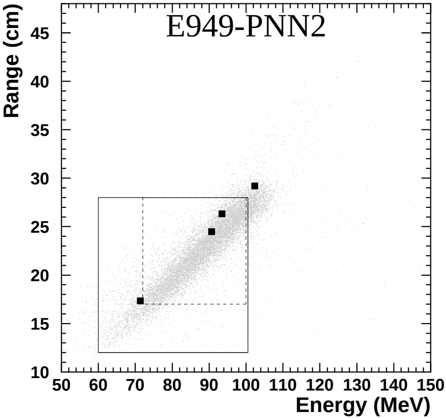


The nine cells

Bkgd	Events	S/B
0.152	0	0.84
0.038	0	0.78
0.019	0	0.66
0.005	0	0.57
0.243	1	0.47
0.059	0	0.45
0.027	1	0.42
0.007	0	0.35
0.379	1	0.20

No momentum cut applied. Solid line represents signal region, dashed line shows tightened kinematic cuts. Gray points are simulated $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$.

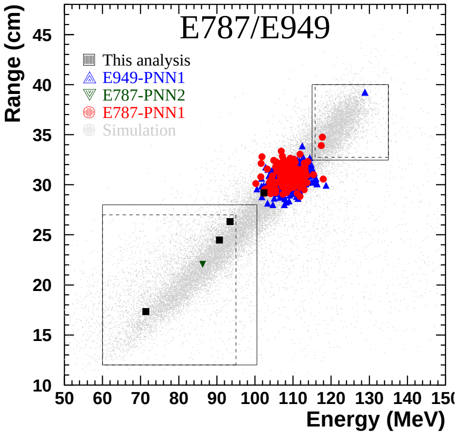
Measured $\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu \bar{\nu})$ for this analysis



All cuts applied.

- $\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu \bar{\nu}) = (7.89^{+9.26}_{-5.10}) \times 10^{-10}$
- The probability of all 3 events to be due to background only is 0.037.
- SM expectation: $\mathcal{B} = (0.85 \pm 0.07) \times 10^{-10}$

Measured $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$ for E949+E787



E787(dashed) and E949(solid) signal regions shown. All cuts applied.

- $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$
- The probability of all 7 events to be due to background only is 0.001.
- SM expectation: $\mathcal{B} = (0.85 \pm 0.07) \times 10^{-10}$
- Despite the size of the boxes in energy *vs.* range, the pnn1 analyses are 4.2 times more sensitive than the pnn2 analyses

What happens next?

- In an ill-considered decision of the Executive Branch of the US Government, E949 was cancelled in 2002 after receiving only 20% of the approved beam time.
- Experiment NA62 (formerly NA48/3) at CERN was approved in 2007 and is in preparation.
- NA62 proposes to observe ≈65 $K^+ \to \pi^+\nu\bar{\nu}$ per year with a background of ≈10 events using a 75 GeV/c beam. The use of kaon decay-in-flight to measure $K^+ \to \pi^+\nu\bar{\nu}$ has not been attempted before.
- There is a letter of intent for a stopped kaon decay experiment in Japan using the best parts of E949.
- "A few % measurement of $K^+ \to \pi^+\nu\bar{\nu}$ appears feasible at Fermilab Project X." - D.Bryman

In 25 years of research with BNL E787 and E949, the search for $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ decays went from a limit on the branching ratio of $< 1.4 \times 10^{-7}$ (90%CL) to a measurement of $(1.73^{+1.15}_{-1.05}) \times 10^{-10}$ (arXiv:0808.2459) that is twice as large as, but still consistent with, the Standard Model expectation of $(0.85 \pm 0.07) \times 10^{-10}$.

The techniques, philosophy and results of E949 and E787 have s(h)own the way for experimental searches of rare decays.

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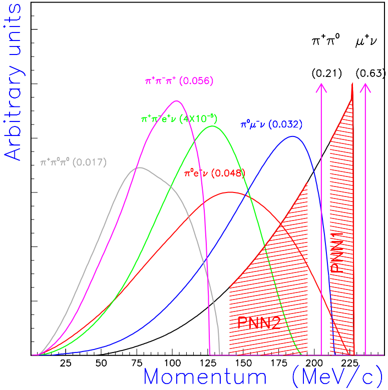
Backgrounds in high momentum (pnn1) region

Mechanisms for the main backgrounds in the high momentum region



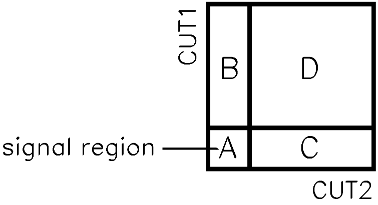
$\mathbf{K^+ \to \pi^+\pi^0}$ **($K_{\pi2}$)**

1. Mismeasurement of π^+ kinematics
2. Undetected photons from $\pi^0 \to \gamma\gamma$

$\mathbf{K^+ \to \mu^+\nu}$ **($K_{\mu2}$)**

1. Mismeasurement of μ^+ kinematics
2. Misidentification of μ^+ as π^+

Estimation of background rates with data



if CUT1, CUT2
uncorrelated,

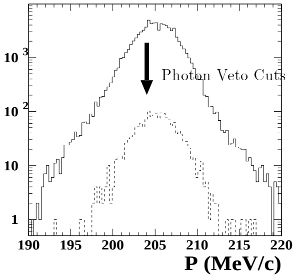
$$A/B = C/D$$

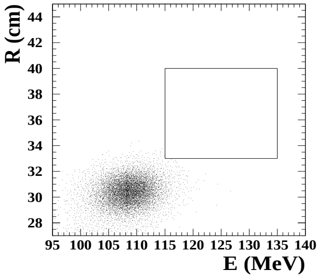
$$A = BC/D$$

- Apply cut2 & invert cut1: Select B events
- Invert cut2: Select C+D events

  & apply cut1: Select C events
- Rejection of cut1 is R = (C+D)/C
- Background estimate = B/(R-1)

Example: Estimating $K^+ \to \pi^+\pi^0$ pnn1 background with data

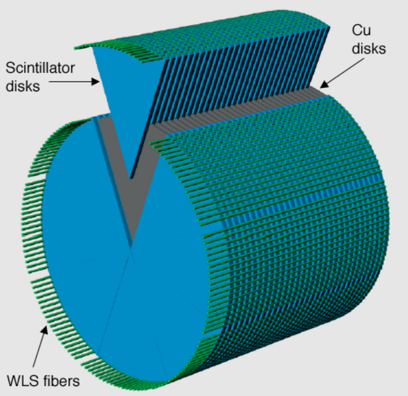




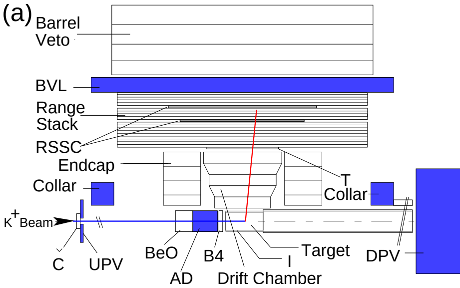
Left: Kinematically selected $K^+ \to \pi^+\pi^0$ with photon veto applied. Photon veto: Typically 2-5 ns time windows and 0.2 - 3 MeV energy thresholds

Right: Select photons. Phase space cuts in P, R, E.

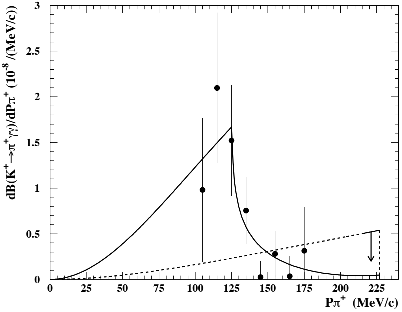
Photon veto in the beam region



Active Degrader (AD)
14cm diameter, 17cm long,
12 azimuthal segments
6.1 radiation lengths



$K^+ \rightarrow \pi^+\gamma\gamma$ is not a background



Ref: E787, PRL **79**, 4079 (1997).

- Partial branching fraction for $140 < P_\pi < 200\ \mathrm{MeV}/c$ is $\approx 1.1 \times 10^{-7}$.
- Photon veto rejection of $\pi^0 \rightarrow \gamma\gamma$ is $> 10^6$.
- Rate of $K^+ \rightarrow \pi^+\gamma\gamma$ background is $< 1.1 \times 10^{-13}$ without considerations of π^+ acceptance.